High-Frequency Muzzle Voltage Measurements

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The muzzle voltage in solid-armature railguns is an important diagnostic because it can provide information about the state of the rail–armature interface. Sudden jumps in the muzzle voltage can indicate that an armature has made a transition from low voltage to arcing contact. However, in many tests, the muzzle voltage increases gradually, and the onset of transition as indicated by the muzzle voltage is ambiguous. This report describes research aimed at developing alternative approaches for detecting the onset of arcing contact in solid armature railguns. The work, conducted at the IAT in the early part of 2006, sought to determine whether there is information in the 20 kHz–500 MHz range of the power spectrum that correlates strongly with the onset of transition to arcing contact. To this end, we analyzed two types of signals collected during railgun tests for information that might indicate the onset of arcing. One was a highfrequency muzzle voltage measurement recorded with a 1 GHz sampling rate. The other signal was broad band electromagnetic (EM) radiation (also sampled at 1 GHz) collected using a 2-meter dipole antenna in the vicinity of the railgun. The results show that there is some correlation between the high-frequency and conventional muzzle voltage measurements, and there is little correlation between the broadband EM radiation measurement and the conventional muzzle voltage measurement. The high-frequency muzzle voltage measurement does not appear to contain information about the electrical state of the rail–armature interface that could be used to indicate the presence of arcing.

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High-Frequency Muzzle Voltage Measurements

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Abstract—The muzzle voltage in solid-armature railguns is an important diagnostic because it can provide information about the state of the rail–armature interface. Sudden jumps in the muzzle voltage can indicate that an armature has made a transition from low voltage to arcing contact. However, in many tests, the muzzle voltage increases gradually, and the onset of transition as indicated by the muzzle voltage is ambiguous. This report describes research aimed at developing alternative approaches for detecting the onset of arcing contact in solid armature railguns. The work, conducted at the IAT in the early part of 2006, sought to determine whether there is information in the 20 kHz–500 MHz range of the power spectrum that correlates strongly with the onset of transition to arcing contact. To this end, we analyzed two types of signals collected during railgun tests for information that might indicate the onset of arcing. One was a high-frequency muzzle voltage measurement recorded with a 1 GHz sampling rate. The other signal was broad band electromagnetic (EM) radiation (also sampled at 1 GHz) collected using a 2-meter dipole antenna in the vicinity of the railgun. The results show that there is some correlation between the high-frequency and conventional muzzle voltage measurements, and there is little correlation between the broadband EM radiation measurement and the conventional muzzle voltage measurement. The high-frequency muzzle voltage measurement does not appear to contain information about the electrical state of the rail–armature interface that could be used to indicate the presence of arcing.

Key words: muzzle voltage; solid-armature railgun; transition to arcing contact; RF; railgun diagnostics; railgun instrumentation

1. Introduction to Muzzle Voltage

The muzzle voltage of a railgun is the potential difference between the rails measured at the muzzle of the gun. It is a useful diagnostic tool for railgun research because it can be used to identify the point at which an armature makes a transition from solid or liquid metal-to-metal contact with the rails to arcing contact. During transition a plasma arc forms between the armature and typically one of the rails. The time scale for forming the plasma is relatively short, on the order of tens of microseconds, and the plasma is significantly more resistive than the metal-to-metal contact that it replaces. This is reflected as an increase in the muzzle voltage over a short period of time. The increase in amplitude that occurs after transition reflects an increase in the voltage drop of the plasma.

2. Conventional Muzzle Velocity Measurement

The standard technique for making muzzle voltage measurements at the Institute for Advanced Technology (IAT) laboratory is shown in Figure 1. The technique involves placing a current viewing resistor, R, typically on the order of 100 Ω, across the muzzle and measuring the current through the resistor with a current transformer, such as a Pearson coil. The output of the Pearson coil is a voltage that is proportional to the voltage drop across the resistor. This technique has the benefit of making a floating voltage measurement, since diagnostic grounds (specifically, ground loops) can be detrimental. The drawback of this technique is that the bandwidth of the measurement is limited to about 10 kHz by the characteristics of the current transformer.

This technique has been adequate for diagnosing transition on the IAT's 40 mm medium caliber launcher (MCL), for which transition typically involves a sudden and significant increase in the amplitude of the muzzle voltage. The technique, however, produces a less precise diagnostic for transition on IAT's larger launcher—the 55 mm high-energy medium caliber launcher (HEMCL). On this launcher, the muzzle voltage traces tend to increase gradually, and in general do not indicate a clearly identifiable onset of transition. A second limitation is that the arrangement described in Figure 1 cannot be used as a diagnostic for transition if a muzzle shunt is present.

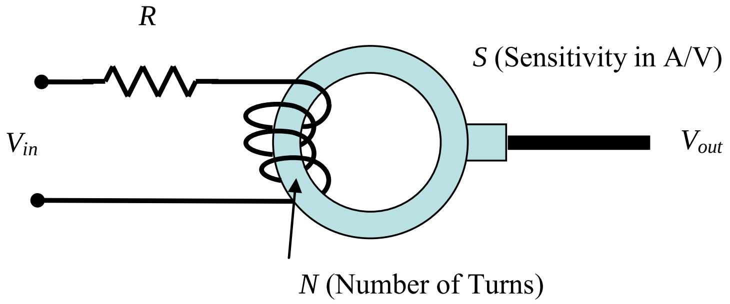

Figure 1. Schematic of Pearson coil to measure muzzle voltage.

3. High-Frequency Muzzle Velocity Measurement

For these reasons, we have begun to look for alternative techniques for detecting the onset of transition. This report describes work conducted at the IAT in the early part of 2006 to determine whether there might be information in the 20 kHz–500 MHz range of the frequency spectrum that correlates strongly enough with the onset of transition that it can be developed into a reliable diagnostic.

We analyzed two types of signals collected during railgun tests for information that might correlate with onset of transition. One of the signals was a high bandwidth muzzle voltage measurement recorded at a sampling rate of 1 GHz. The other was a measurement of broad-band electromagnetic (EM) radiation collected using a 150 MHz dipole antenna in the vicinity of the railgun.

Because the Pearson transformer typically used to measure the muzzle voltage also acts as a low-pass filter, it was not used to measure the high-frequency components. Instead, the high-frequency components of the muzzle voltage (V1) were recorded across the 50 Ω resistance of the scope, labeled R3 in the schematic in Figure 2. The amplitude of the relative frequency response of this circuit is shown at the bottom of Figure 2. Here, resistors R1, R2 (each 5000 Ω) form a 10000:50 resistor divider network with R3. The capacitors C1 and C2 = 2.7 nF isolate the oscilloscope from excessive, low-frequency voltage components at the muzzle.

Broadband EM Radiation Measurement

We also collected broad-band EM radiation in the vicinity of the launcher using the 150 MHz dipole antenna shown in Figure 3. Because the high-frequency components are weak, the signal was first amplified with a 20 dB broad-band amplifier. A four-pole, 100 MHz high-pass filter was also present to prevent saturation of the amplifier from the higher level, low-frequency components.

Results

We collected muzzle velocity time series and EM radiation from three consecutive tests of the HEMCL. Table I summarizes the standard muzzle voltage measurements. The tests were conducted at different conditions, so the peak current, muzzle velocity, and the point of transition were different for each shot.

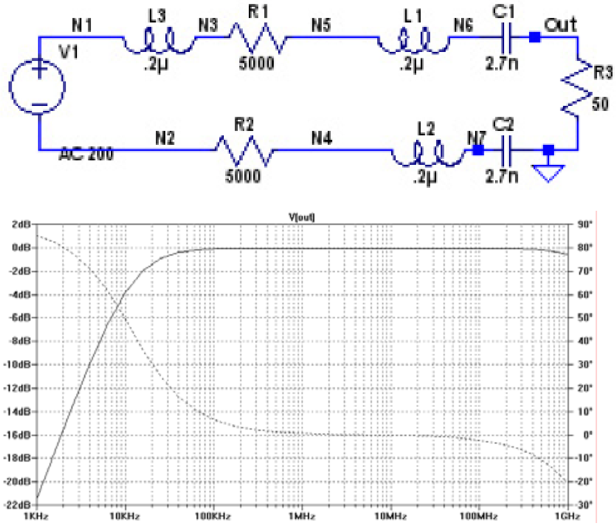

Figure 2 Arrangement used to make high-frequency muzzle voltage measurements. The relative output voltage amplitude (solid) and phase (dashed) vs. frequency 1 kHz–1 GHz of the recorded output signal are shown below.

Figure 3. Antenna used to measure broad band RF radiation present during the tests. The signal is directly applied to a 100 MHz high-pass filter and 20 dB broadband amplifier (close-up at the right) before transmission via RG-8 coax to the digital oscilloscope.

Table I. Summary of Test Conditions and Results for HEMCL 380, 381, and 382

Shot Number	Peak Current (MA)	Muzzle Velocity (km/s)	*t1*: Time to Steel Cladding (ms)	*t2*: Time to First Transition Spike (ms)	*t3*: Time of Muzzle Exit (ms)
380	1.32	1.60	2.1 ± 0.1	3.8	4.13
381	1.53	1.90	1.9 ± 0.1	2.49	3.42
382	1.77	2.14	1.7 ± 0.1	2.40	3.09

The launch package used in the tests was the 754-gram version of the HEKJ armature, a research armature that has been used at the IAT in hundreds of experiments. The principal transition mechanism for this armature is an electrodynamic effect associated with the rapid reduction in current [6].

The muzzle voltage time series for the three tests were obtained by both conventional means (labeled as standard) and by the high-frequency technique, and are shown together in a single plot in Figure 4. In the figure, the muzzle voltages obtained by conventional means are shown in the top half of the plot with the three significant peaks noted. The peaks for each muzzle voltage trace occurs at *t1*, the time at which the armature passed over a change in the resistivity of the rails; *t2*, the time when a first distinct, transition-like spike is seen; and *t3*, the time of muzzle exit, as indicated by a rapid rise in the muzzle voltage to over 1500 V. These times are also listed in Table I.

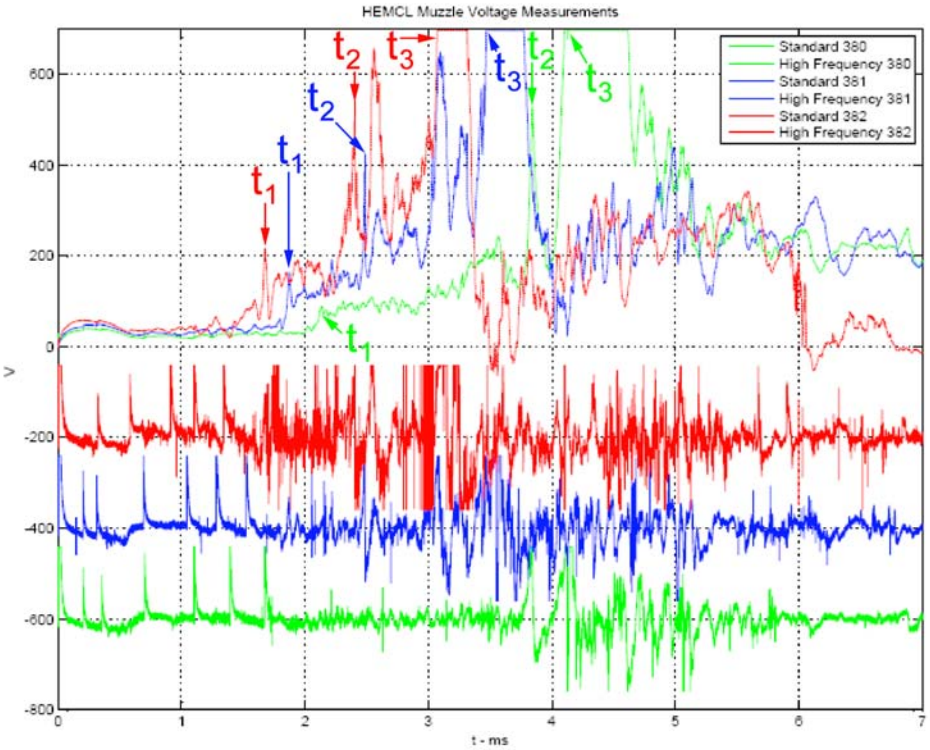

Figure 4. Muzzle voltage signals from MCL shots 380, 381, 382. The traces measured using the conventional approach are shown in the top half of the plot, while the traces measured by preserving high-frequency components are shown in the bottom half of the plot with negative voltage offsets.

While a comparison of corresponding muzzle voltage time-series in Figure 4 shows some correlation between high-frequency and conventional muzzle voltage measurements, the significant peaks are *not* more distinguishable using the higher frequency technique. In fact, the high-frequency method results in many additional peaks, making it more difficult to identify them.

Spectral analyses were conducted in an effort to gather more insight. Spectrograms (sequential power spectra computed using short-time FFTs) were calculated and are shown in Figures 5a, 6a, and 7a as contour plots of the high-frequency muzzle voltage measurements for the three tests, respectively. The contours show signal strength in dB as a function of time and frequency. The timing of three events listed Table I is also indicated on each plot. Figures 5b, 6b, and 7b are corresponding plots of the high-frequency EM radiation.

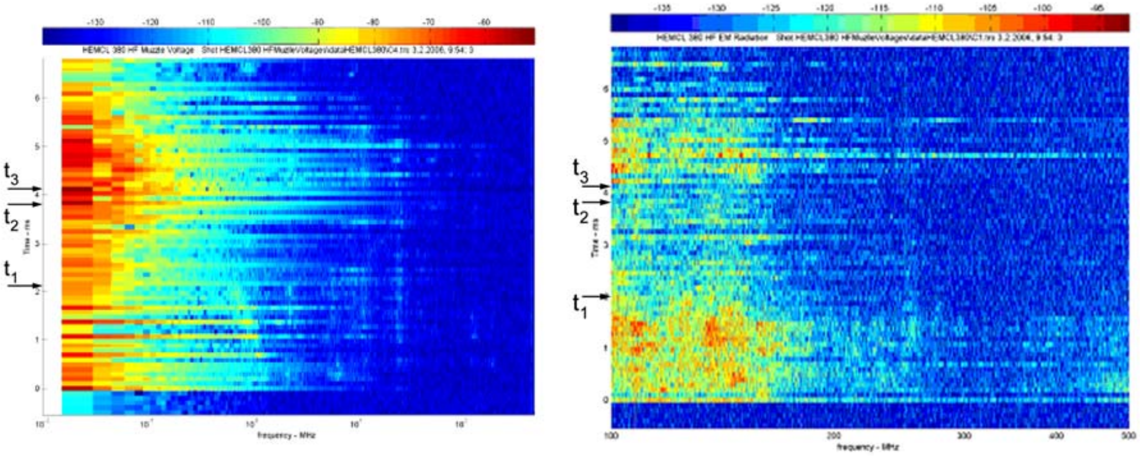

Figure 5. Spectrogram of HEMCL 380: high-frequency muzzle voltage (left) and EM radiation (right).

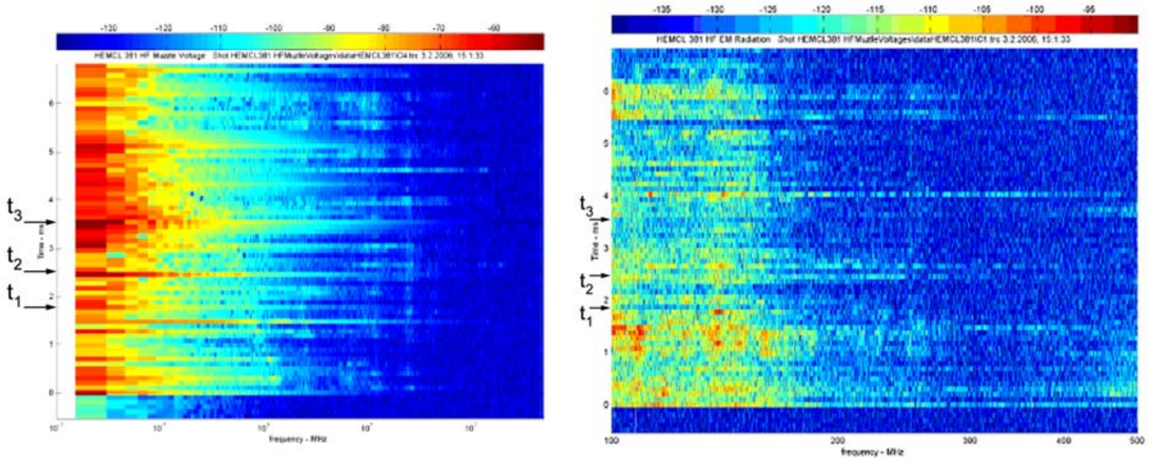

Figure 6. Spectrogram of HEMCL 381: high-frequency muzzle voltage (left) and EM radiation (right).

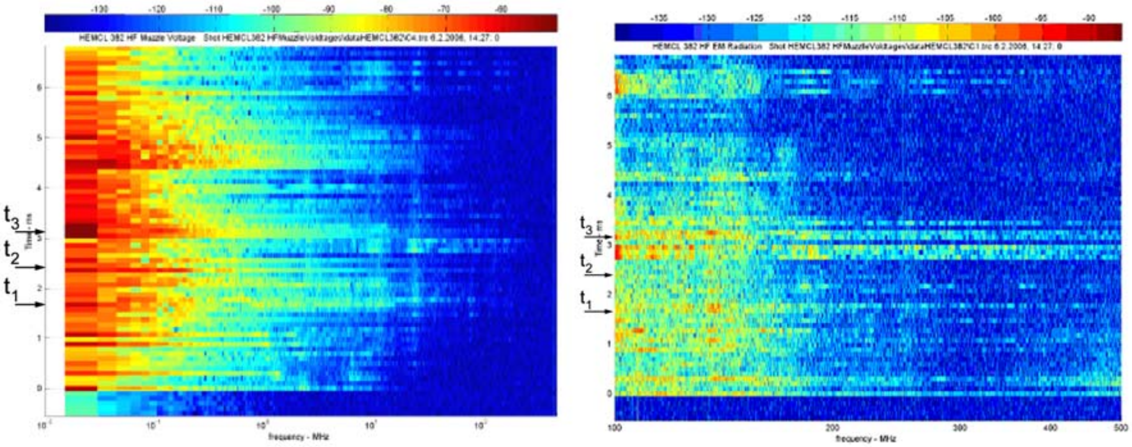

Figure 7. Spectrogram of HEMCL 382: high-frequency muzzle voltage (left) and EM radiation (right).

Analysis of the high-frequency muzzle voltage and EM radiation spectrograms do not appear to present any more identifiable features than conventional muzzle voltage measurements - as relating to the significant features usually associated with: *t*1— passage over a change in rail resistivity; *t*2—the first distinct, transition-like spike, and *t*3—the time of muzzle exit.

Discussion and Conclusion

The purpose of this investigation was to search for features in the 10 kHz–500 KHz muzzle voltage frequency bands that are more easily identifiable than important peaks found at lower frequencies. Correlation between the high-frequency and low-frequency muzzle voltage measurements was expected since they are measurements of the same signal. The correlation is apparent in the spectral plots for all three tests, in Figures 5a, 6a, and 7a for second and third significant spikes, *t2* and *t3*. These appear as dark brown contours indicating high amplitude at the lowest frequency band plotted. The high-frequency measurements show no increase in amplitude when the armature crosses the point at which the resistivity of the rails changes, since this passage does not create a plasma (that we know of). Our hope however was to find a robust indicator of transition, rather than just evidence of correlation between the high-frequency and low-frequency muzzle voltage components. We did not find such an indicator.

There are issues that may have complicated this work making the results inconclusive. The onset of arcing contact tends to be ambiguous in the HEMCL as compared to the MCL launcher which usually has a more sharply defined transition event. There was the possible presence of broadband noise due to arcing at locations other than the rail–armature interface. For example, attempts to measure light emissions from the bore of the railgun have found the presence of arcing from the time the first capacitor banks are discharged at the breech. Arcing greatly reduces the signal to noise ratio in the measurement.

Finally, theoretical considerations suggest that railgun plasmas should radiate at significantly higher frequencies than those measured. The lowest characteristic frequency for a railgun plasma is the cyclotron frequency (~500 MHz), which is three orders of magnitude greater than the highest frequency of the measurements reported here. It is in this higher frequency range that a future, alternative technique for detecting the onset of transition should be considered.

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